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Noise Prediction for Hydrophone/Preamplifier Systems

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PREFACE

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This report describes a simulation model used for calculating the electronic noise from the combination of an amplifier and a capacitive sensor such as a sonar hydrophone. Two cases are examined: a non-inverting amplifier with high input impedance and an inverting amplifier with low input impedance. The inverting amplifier is sometimes referred to as a charge amplifier since it uses capacitive feedback in conjunction with the capacitive source to establish voltage gain. The significant noise sources used in the model are the same for the inverting and non-inverting cases. These noise sources include thermal noise from the hydrophone, thermal noise from resistors, and voltage and current noise from the amplifier.

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INTRODUCTION

This report describes a simulation model used for calculating the electronic noise from the combination of an amplifier and a capacitive sensor such as a sonar hydrophone. Two cases are examined: a non–inverting amplifier with high input impedance and an inverting amplifier with low input impedance. The inverting amplifier is sometimes referred to as a charge amplifier since it uses capacitive feedback in conjunction with the capacitive source to establish voltage gain. The significant noise sources used in the model are the same for the inverting and non–inverting cases. These noise sources include thermal noise from the hydrophone, thermal noise from resistors, and voltage and current noise from the amplifier.

The noise sources are treated as independent sources. In the development of the equations for the noise referred to the hydrophone input, the transfer function from the hydrophone input to the amplifier output is first derived. Then the transfer functions from each of the noise sources to the amplifier output are derived and the amplifier noise outputs are power summed. Finally, the total output noise is divided by the hydrophone signal transfer function to arrive at the total noise referred to the hydrophone input. By examining noise at the hydrophone input, comparisons can be readily made between differing hydrophone and amplifier parameters and against a common acoustic noise standard such as sea state zero. Examination of the two amplifier configurations shows nearly identical signal–to–noise ratio.

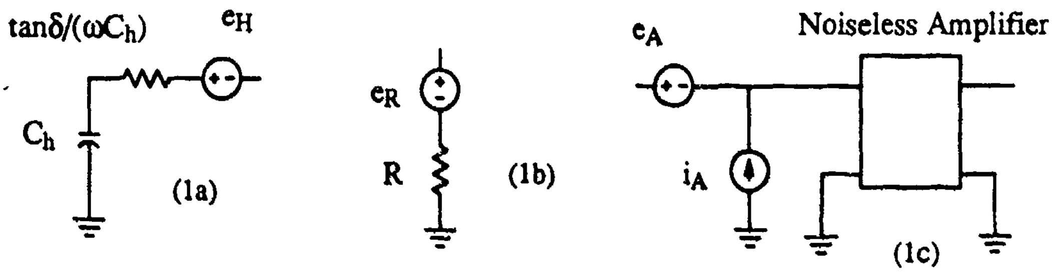
A standard ambient acoustic ocean noise model is described which is useful for evaluating the relative merits of various hydrophone/amplifier configurations [1]. The ambient acoustic noise chosen for an example in this report consists of sea state zero, shipping density I, low frequency ocean turbulence and molecular agitation. When comparing electronic noise with acoustic signals or with ambient acoustic noise, this model is only valid when the hydrophone is omnidirectional. For the case where the hydrophone is not omnidirectional, the reader is referred to [2].

Eight simulation examples are shown for various hydrophone and amplifier parameters. A main simulation program and three subprograms which implement the noise model have been written using the MATLAB analysis program and will be discussed later. Requests for a copy of the MATLAB programs using electronic mail may be addressed to the author at "straw@nl.nuwc.navy.mil". The last two simulation examples include test measurements taken from preamplifiers with a capacitor simulating the hydrophone impedance. In these two examples, the simulation program was modified to display noise at the amplifier input in units of dBV/$\sqrt{\text{Hz}}$.

It is important to note that this model applies to a single channel with an omnidirectional hydrophone. To generalize this model to the case where many channels of hydrophone/amplifier are combined in a beamformer, it is necessary to include the fact that at low frequencies the electronic noise will remain uncorrelated whereas the acoustic ambient noise will experience some spatial correlation due to the oversampling of the acoustic wave. A method for comparing acoustic versus electronic noise at the beamformer output is described in [3].

NOISE SOURCES

Figure 1 shows noise source circuit models foı the typical hydrophone/cable/ amplifier systems which are covered in this paper. The hydrophone is modeled as a voltage generator representing the acoustic to electrical transduction and an internal impedance. The real part of the hydrophone impedance exhibits thermal noise. Discrete resistances are used in the noise model and also exhibit thermal noise. The total amplifier noise is lumped at the amplifier input and is represented by two noise sources.



C_h = Hydrophone Capacitance
$\tan\delta$ = Hydrophone dielectric dissipation factor
ω = Frequency
e_H = Hydrophone thermal noise
R = Discrete resistance (Ohm)
e_R = Discrete resistance noise
e_A = Amplifier voltage noise
i_A = Amplifier current noise

Figure 1. Noise Models for: (1a) Hydrophone, (1b) Discrete resistor and (1c) Amplifier

HYDROPHONE NOISE

The electrical noise from the hydrophone in the stiffness-controlled regime is thermal noise due to the electrical and mechanical losses in the hydrophone. Detailed descriptions of hydrophone noise are contained in section 5.2 of [4] and alos in [2], [5] and [6]. For this analysis the hydrophone impedance is represented as a capacitance and a frequency-dependent series resistance. The thermal noise spectral density of the real part of the hydrophone impedance in a one hertz band is a function of the hydrophone reactance, the hydrophone dielectric dissipation factor (tanδ) and frequency, and is

$$e_H^2 = \frac{4KT\ \tan\delta}{\omega C_h} \quad V^2/Hz \tag{1}$$

where K is the Boltzmann constant (1.38×10^{-23} Joules/Kelvin) and T is temperature in Kelvins.

If p^2_H represents the hydrophone electrical noise power spectral density referred to the hydrophone input and M is the hydrophone sensitivity, then

$$p_H^2 = \frac{e_H^2}{M^2} = \frac{4KT\ \tan\delta}{\omega M^2 C_h} \quad uPa^2/Hz\ . \tag{2}$$

The term M^2C_H is an expression for the hydrophone figure of merit and is a constant for a given volume of material. If the hydrophone volume is equal to V_h, then the hydrophone noise becomes

$$p_H^2 = \frac{4KT\ tan\delta}{\omega V_h} \quad \text{uPa}^2/\text{Hz} \tag{3}$$

which is a function only of temperature, frequency, a hydrophone material parameter (tanδ) and the volume of the hydrophone. Thus the hydrophone noise is independent of wiring configurations such as series–parallel combinations of a group of hydrophone elements. This noise places a fundamental limit on the achievable system noise floor.

RESISTOR NOISE

The non–inverting amplifier configuration uses a resistor to provide a path to ground for amplifier input leakage current and to bleed–off accumulated DC charge from the hydrophone. The inverting amplifier configuration uses a resistor in the feedback path to stabilize the DC operating point. The noise spectral density from a discrete resistor is

$$e_R^2 = 4KTR \quad \text{V}^2/\text{Hz}. \tag{4}$$

AMPLIFIER NOISE

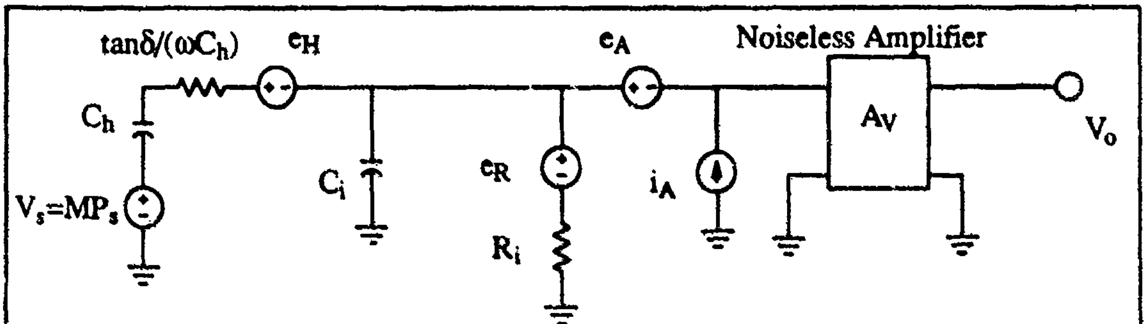
The amplifier is modeled as a noiseless gain stage preceded by two uncorrelated noise sources [7]. These two sources ideally represent all of the noise in the signal acquisition system, including the preamplifier, filter stages, step gain stages, and possibly quantization error noise from an analog–to–digital converter. Thus the term "amplifier noise" can refer to just the noise from the preamplifier, or to all of the noise in a system. If a step gain stage is used, then the noise levels referred to the input will likely be a function of the gain setting. Early in system design, it is not possible to measure the referred–to–input noise from the system and thus careful modelling of each of the stages must be performed in order to arrive at useful values of amplifier voltage and current noise. Amplifier noise modeling and measurement is described in [4], [7] and [8]. For this analysis, the voltage noise spectral density from the amplifier is represented by a white noise region above ω_o with spectral noise level of e_o^2 and a $1/f^\alpha$ noise region below ω_o with a slope characterized by α. The voltage noise spectral density from the amplifier is

$$e_A^2 = \left(1 + \left(\frac{\omega_o}{\omega}\right)^\alpha\right) e_o^2 \quad \text{V}^2/\text{Hz}. \tag{5}$$

The current noise spectral density from the amplifier is assumed to be white for this analysis and is represented by a single, frequency–independent quantity i_o^2. This assumption may not be valid at frequencies above a few kHz and thus may require additional analysis and measurement.

NON–INVERTING AMPLIFIER NOISE MODEL

Figure 2 shows a circuit model for the impedances and noise sources in a hydrophone/cable/amplifier system with a non–inverting amplifier. The hydrophone is modeled as a voltage generator representing the acoustic to electrical transduction, and a capacitor and resistor representing the internal impedance of the hydrophone. The internal hydrophone losses exhibit thermal noise which is represented by e_H. The cable is modeled as a capacitance which is lumped with the amplifier input capacitance, C_i. Cable leakage resistance is lumped with the amplifier input resistance, R_i. The amplifier is represented by a noiseless gain stage preceded by two noise sources. Each of these model elements is discussed in more detail in the following sections.



P_s = Hydrophone input signal (acoustic)
V_s = Hydrophone output signal (electric)
M = Hydrophone sensitivity
C_h = Hydrophone capacitance
$\tan\delta$ = Hydrophone dielectric dissipation factor
e_H = Hydrophone thermal noise spectrum level
C_i = Amplifier plus cable input capacitance
R_i = Amplifier plus cable input resistance
e_R = Input resistance noise
e_A = Amplifier voltage noise
i_A = Amplifier current noise
A_v = Amplifier closed loop voltage gain (a function of frequency)
ω = Frequency

Figure 2. Hydrophone/Cable/Non–inverting Amplifier Noise Model

TRANSFER FUNCTION FOR THE SIGNAL AND NOISE SOURCES

By using linear circuit analysis techniques, the transfer function from the hydrophone signal and from each noise source to the amplifier output can be derived. When calculating the transfer functions for the noise model the hydrophone dissipation factor $\tan\delta$ is ignored since it is typically less than 0.02. The dissipation factor is still included in the self–noise calculation for the hydrophone. The derivation of the transfer function from the hydrophone signal output to the amplifier output is shown in Appendix A. The transfer function for the noise sources are derived in a similar manner to that shown in Appendix A. The transfer function from the hydrophone acoustic signal input to the amplifier output is

$$\frac{V_{o_s}}{P_s} = A_v \frac{M}{\frac{C_h + C_i}{C_h} + \frac{1}{j\omega C_h R_i}} \quad . \tag{6}$$

The transfer function from the hydrophone thermal noise source (i.e. the noise due to the real part of the hydrophone impedance) to the amplifier output is

$$\frac{V_{o_H}}{e_H} = A_v \frac{1}{\frac{C_h + C_i}{C_h} + \frac{1}{j\omega C_h R_i}} \quad , \tag{7}$$

the transfer function from the amplifier voltage noise source to the amplifier output is

$$\frac{V_{o_A}}{e_A} = A_v \quad , \tag{8}$$

the transfer function from the input resistor noise source to the amplifier output is

$$\frac{V_{o_R}}{e_R} = A_v \frac{1}{1 + j\omega R_i (C_h + C_i)} \quad , \tag{9}$$

and the transfer function from the amplifier current noise source to the amplifier output is

$$\frac{V_{o_I}}{i_A} = A_v \frac{R_i}{1 + j\omega R_i (C_h + C_i)} \quad . \tag{10}$$

TOTAL NOISE REFERRED TO HYDROPHONE INPUT

Although the amplifier voltage and current noise sources are sometimes correlated, assuming that they are not so results in little or no error [4, pg. 5–7]. The total amplifier output is then the power sum of the outputs from each of the noise components and is

$$|V_{o_T}|^2 = |V_{o_H}|^2 + |V_{o_A}|^2 + |V_{o_R}|^2 + |V_{o_I}|^2 \quad . \tag{11}$$

The composite of all noise sources referred to the hydrophone input is equal to the total output noise (11) divided by the hydrophone signal transfer function (6) squared and is

$$P_{I_T}^2 = \left(\frac{P_s}{V_{o_s}}\right)^2 |V_{o_T}|^2$$

$$= \left(\frac{P_s}{V_{o_s}}\right)^2 \left(|V_{o_H}|^2 + |V_{o_A}|^2 + |V_{o_R}|^2 + |V_{o_I}|^2\right)$$

$$= \left[\frac{\frac{C_h + C_i}{C_h} + \frac{1}{j\omega C_h R_i}}{A_v M}\right]^2 \left(|V_{o_H}|^2 + |V_{o_A}|^2 + |V_{o_R}|^2 + |V_{o_I}|^2\right) \quad . \tag{12}$$

Using the expressions for the noise terms shown in equations (1) to (5) and taking the magnitudes of equations (6) to (10), the power sum of all noise components referred to the hydrophone input is

$$P_{I_T}^2 = \frac{4KT\ \tan\delta}{\omega M^2 C_h} + \frac{1}{M^2}\left[\left(\frac{C_h + C_i}{C_h}\right)^2 + \frac{1}{\left(\omega R_i C_h\right)^2}\right]\left(1 + \left(\frac{\omega_o}{\omega}\right)^a\right)e_o^2 \tag{13}$$

$$+ \frac{1}{M^2}\frac{1}{1 + \left(\omega R_i\left(C_h + C_i\right)\right)^2}\left[\left(\frac{C_h + C_i}{C_h}\right)^2 + \frac{1}{\left(\omega R_i C_h\right)^2}\right]\left(4KTR_i + i_A^2 R_i^2\right) .$$

The above expression can be simplified if one is only interested in frequencies above the corner frequency formed by the hydrophone capacitance and the input resistor which is typically at or below the lowest frequency of interest. Thus, for $\omega > 3/R_iC_h$,

$$P_{I_T}^2 \approx \frac{4KT\ \tan\delta}{\omega M^2 C_h} + \frac{1}{M^2}\left(\frac{C_h + C_i}{C_h}\right)^2\left(1 + \left(\frac{\omega_o}{\omega}\right)^a\right)e_o^2$$

$$+ \frac{1}{M^2}\left(\frac{4KT}{R_i} + i_A^2\right)\left(\frac{1}{\omega C_h}\right)^2 \quad \mathrm{uPa^2/Hz}\ . \tag{14}$$

OBSERVATIONS

Several interesting observations are noted in the simplified noise expression (14) which describes the electronic noise referred to the hydrophone input:

1. The first term in (14) is the noise due to the hydrophone internal losses and is independent of any cable or preamplifier parameters. This noise sets a fundamental limit on the performance of the system signal to noise ratio. This noise power is proportional to $1/\omega$ and thus varies with frequency by –10 dB/decade.
2. The second term in (14) is due to the voltage noise e_o. This noise has a flat spectrum above ω_o (typically 500 to 2000 Hz) and a slope of $-10\cdot\alpha$ dB/decade below ω_o. The slope $10\cdot\alpha$ is highly dependant on preamplifier implementation and can vary from 5 to 30 dB/decade. The voltage noise referred to the hydrophone input is increased by a factor

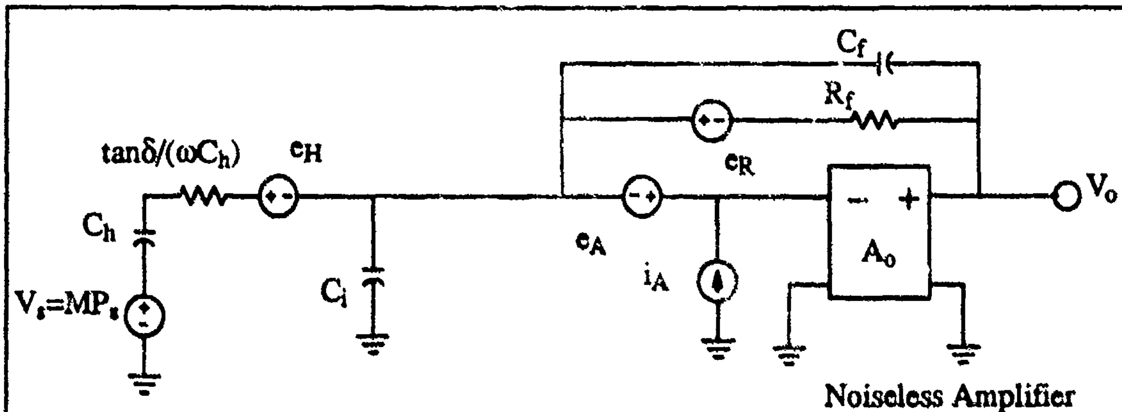
depending on cable plus input capacitance C_i and thus to minimize this effect C_i should be kept small compared to the hydrophone capacitance.

3. The third term in (14) is due to noise from two sources: the input resistor R_i and the amplifier current noise i_A. For frequencies above $1/R_iC_h$ the noise from the input resistor behaves like a current source. The input resistor noise power is proportional to $1/R_i$ and is reduced by increasing the value of R_i. This noise power is proportional to $1/\omega^2$ and thus varies with frequency by –20 dB/decade.

4. Since the different noise sources have different slopes versus frequency, it is reasonable to assume that there will be regions where the noise from one mechanism is dominant. This observation will be explored further in the section on examples.

INVERTING AMPLIFIER NOISE MODEL

Figure 3 shows a circuit model for the impedances and noise sources in a hydrophone/cable/amplifier system with an inverting amplifier. In this configuration the voltage gain of the hydrophone signal is set by the ratio of the two capacitors C_h and C_f. The hydrophone is modeled as a voltage generator representing the acoustic to electrical transduction and a capacitor and resistor representing the internal impedance of the hydrophone. The internal hydrophone losses exhibit thermal noise which is represented by e_H. The cable is modeled as a capacitance which is lumped with the amplifier input capacitance, C_i. The amplifier is modeled in a closed–loop form to take into account the charge amplification. For noise calculation purposes, the cable leakage resistance is lumped with the amplifier feedback resistance, R_f. (Both of these resistors inject noise current into the amplifier input summing node). The amplifier is represented by a noiseless stage preceded by two noise sources. Each of these model elements is discussed in more detail in the following sections.



P_s = Hydrophone input signal (acoustic)
V_s = Hydrophone output signal (electric)
M = Hydrophone sensitivity
C_h = Hydrophone capacitance
$\tan\delta$ = Hydrophone dielectric dissipation factor
e_H = Hydrophone thermal noise spectrum level
C_i = Amplifier plus cable input capacitance
C_f = Amplifier feedback capacitance
R_f = Amplifier feedback plus cable leakage resistance
e_R = Feedback resistance noise
e_A = Amplifier voltage noise
i_A = Amplifier current noise
A_o = Amplifier open loop voltage gain (a function of frequency)
ω = Frequency

Figure 3. Hydrophone/Cable/Amplifier Noise Model

TRANSFER FUNCTION FOR THE SIGNAL AND NOISE SOURCES

By using linear circuit analysis techniques, the transfer function from the hydrophone signal and from each noise source to the amplifier output can be derived. The open loop gain of the amplifier is A_o. When calculating the transfer functions for the noise model the hydrophone dissipation factor tanδ is ignored since it is typically less than 0.02. The dissipation factor is still included in the self-noise calculation for the hydrophone. The derivation of the transfer function from the hydrophone signal output to the amplifier output is shown in Appendix B. The transfer function for the noise sources are derived in a similar manner to that shown in Appendix B. The transfer function from the hydrophone acoustic signal input to the amplifier output is

$$\frac{V_{o_s}}{P_s} = \frac{C_h}{C_f}\left(\frac{M}{D}\right) , \tag{15}$$

where

$$D = -1\left\{1 + \frac{1}{A_o}\left(\frac{C_h + C_i}{C_f}\right) + \frac{1}{j\omega R_f C_f}\right\} . \tag{16}$$

The transfer function from the hydrophone thermal noise source (i.e. the noise due to the real part of the hydrophone impedance) to the amplifier output is

$$\frac{V_{o_H}}{e_H} = \frac{C_h}{C_f}\left(\frac{1}{D}\right) , \tag{17}$$

the transfer function from the amplifier voltage noise source to the amplifier output is

$$\frac{V_{o_A}}{e_A} = \frac{C_h + C_i + C_f}{C_f}\left(1 + \frac{1}{j\omega R_f(C_h + C_i + C_f)}\right)\left(\frac{1}{D}\right) , \tag{18}$$

the transfer function from the feedback resistor noise source to the amplifier output is

$$\frac{V_{o_R}}{e_R} = \frac{1}{j\omega R_f C_f}\left(\frac{1}{D}\right) , \tag{19}$$

and the transfer function from the amplifier current noise source to the amplifier output is

$$\frac{V_{o_I}}{i_A} = \frac{1}{j\omega C_f}\left(\frac{1}{D}\right) . \tag{20}$$

TOTAL NOISE REFERRED TO HYDROPHONE INPUT

Although the amplifier voltage and current noise sources are sometimes correlated, assuming that they are not so results in little or no error [4, pg.5–7]. The total amplifier output is then the power sum of the outputs from each of the noise components and is

$$|V_{o_T}|^2 = |V_{o_H}|^2 + |V_{o_A}|^2 + |V_{o_R}|^2 + |V_{o_I}|^2 \quad . \tag{21}$$

The composite of all noise sources referred to the hydrophone input is equal to the total output noise (21) divided by the hydrophone signal transfer function (15) and (16) squared and is

$$\begin{aligned} P^2_{I_T} &= \left(\frac{P_s}{V_{o_s}}\right)^2 |V_{o_T}|^2 \\ &= \left(\frac{P_s}{V_{o_s}}\right)^2 \left(|V_{o_H}|^2 + |V_{o_A}|^2 + |V_{o_R}|^2 + |V_{o_I}|^2\right) \\ &= \left(\frac{C_f}{C_h} D\right)^2 \left(|V_{o_H}|^2 + |V_{o_A}|^2 + |V_{o_R}|^2 + |V_{o_I}|^2\right) \quad . \end{aligned} \tag{22}$$

Using the expressions for the noise terms shown in (1) to (5) and taking the magnitudes of equations (15) to (20), the power sum of all noise components is

$$\begin{aligned} P^2_{I_T} = {} & \frac{4KT\ \tan\delta}{\omega M^2 C_h} + \frac{1}{M^2}\left[\frac{C_h + C_i + C_f}{C_h}\right]^2 \left[1 + \frac{1}{\omega R_f\left(C_h + C_i + C_f\right)^2}\right]\left(1 + \left(\frac{\omega_o}{\omega}\right)^a\right) e_o^2 \\ & + \frac{1}{M^2}\frac{1}{\left(\omega R_f C_h\right)^2}\left(4KTR_f + i_A^2 R_f^2\right) \quad . \end{aligned} \tag{23}$$

The above expression is simplified by first multiplying the third term through by R^2_f and then noting that $1/R_f(C_h + C_i + C_f)$ is typically below the lowest frequency of interest. For this case

$$\begin{aligned} P^2_{I_T} \approx {} & \frac{4KT\ \tan\delta}{\omega M^2 C_h} + \frac{1}{M^2}\left[\frac{C_h + C_i + C_f}{C_h}\right]^2 \left(1 + \left(\frac{\omega_o}{\omega}\right)^a\right) e_o^2 \\ & + \frac{1}{M^2}\frac{1}{\left(\omega C_h\right)^2}\left[\frac{4KT}{R_f} + i_A^2\right] \quad . \end{aligned} \tag{24}$$

OBSERVATIONS

Several interesting observations are noted in the simplified noise expression (24) which describes the electronic noise referred to the hydrophone input. Note that the hydrophone internal noise and preamplifier current noise effects are identical to the case for the voltage input preamplifier (14) and that the preamplifier voltage noise is nearly identical.

1. The first term in (24) is the noise due to the hydrophone internal losses and is independent of any cable or preamplifier parameters. This noise sets a fundamental limit on the performance of the system signal to noise ratio. Also note that this noise power is proportional to $1/\omega$ and thus varies with frequency by −10 dB/decade.
2. The second term in (24) is due to the voltage noise e_0. This noise has a flat spectrum above ω_0 (typically 500 to 2000 Hz) and a slope of $-10{\cdot}\alpha$ dB/decade below ω_0. The slope $10{\cdot}\alpha$ is highly dependant on preamplifier implementation and can vary from 5 to 30 dB/decade. The voltage noise referred to the hydrophone input is increased by a factor depending on cable plus input plus feedback capacitance ($C_i + C_f$). For the case of significant signal gain, Cf is much smaller than Ch and the expression for voltage noise referred to the hydrophone input reduces to that in (14) for the voltage type amplifier. To minimize degradation of signal–to–noise ratio from voltage noise, C_i should be kept small as compared to the hydrophone capacitance.
3. The third term in (24) is due to noise from two sources: the feedback (and cable leakage) resistor R_f and the amplifier current noise i_A. The noise from the feedback resistor behaves like a current source. The feedback resistor noise power is proportional to $1/R_f$ and is minimized by maximizing the value of R_f. Also note that this noise power is proportional to $1/\omega^2$ and thus varies with frequency by −20 dB/decade.
4. Since the different noise sources have different slopes versus frequency, it is reasonable to assume that there will be regions where the noise from one mechanism is dominant. This observation will be explored further in the section on examples.

AMBIENT OCEAN NOISE STANDARDS

In order to compare various combinations of hydrophones and preamplifiers, it is useful to have a standard against which such comparison can be made. One such standard is NUSC Technical Document 7265 [1] which includes tables and equations for the following types and levels of noise:

a. Sea states 0 to 6
b. Shipping levels 0 to VII
c. Ocean turbulence
d. Molecular agitation

The choice has been made in this report to select the minimum ambient acoustic noise level as consisting of Sea state 0, shipping level I, ocean turbulence and molecular agitation. For an omnidirectional hydrophone, the following levels result for the minimum ambient acoustic noise:

Table 1. Average Ambient Spectral Noise Levels

Frequency	Noise level	Frequency	Noise level
Hz	dB//uPa/Hz	Hz	dB//uPa/Hz
1	108.5	500	48.2
2	98.7	1K	44.8
5	85.8	2K	39.9
10	76.0	5K	32.7
20	66.2	10K	27.3
50	61.4	20K	21.8
100	55.0	40K	19.0
200	50.6	100K	25.0

Reference [1] contains equations defining the noise levels as a function of frequency, sea state and shipping level. A MATLAB m–file (subroutine) has been written for the above case of Sea state 0, shipping level I, ocean turbulence, and molecular agitation. This file is included in Appendix A.

For the case of a hydrophone which is not omnidirectional, the directivity factor of the hydrophone must be considered when comparing electronic noise with ambient acoustic noise. A good explanation of this is contained in [2].

SIMULATION EXAMPLES

This section contains six examples of simulations performed using the model and the MATLAB simulator. In each case, the model used was for the non–inverting configuration of amplifier although the inverting amplifier case is equally valid. The first example shows what happens when the same group of hydrophones is wired into a series or parallel configuration. In examples 2 through 5, a single parameter is varied while the other parameters are held constant. In example 6, the individual noise components for a given case are plotted. The following six cases were simulated and are shown on the succeeding pages:

1. Alternate wiring configurations of two hydrophone groups.
2. The effect of input resistance variation on total noise. Examples are shown for 10, 30 and 100 Megohms.
3. The effect of hydrophone capacitance variation on total noise. Examples are shown for 300, 1000 and 3000 picofarads.
4. The effect of hydrophone dielectric loss variation on total noise. Examples are shown for $\tan\delta$ of 0.005, 0.015 and 0.045.
5. The effect of amplifier voltage noise variation on total noise. Examples are shown for –166, –160, and –154 dB//V/$\sqrt{\text{Hz}}$.
6. An illustration of the individual noise components and total noise.

Each of the following six simulation examples includes a dashed curve labeled "SS0/SL1" which corresponds to an ambient acoustic background noise of Sea State 0, Shipping Level 1, and Ocean Turbulence as defined in [1]. Molecular Agitation was not included in these examples since it is not significant at these frequencies.

The first example looks at a non–inverting amplifier and a group of hydrophones over the frequency range from 10 Hz to 10 kHz. The group of hydrophones is being examined in two different wiring configurations to see the effect of higher capacitance (case I parallel wired elements) versus higher sensitivity (case II series wired elements). The amplifier noise parameters are typical for a sonar preamplifier. Figure 4 was generated using the program "hypA1.m" and subprograms "hypall.m" and "ss0sl1.m" shown in Appendix C.

Table 2. Model Parameters for Alternate Hydrophone Wiring Configurations

Parameter		Units	Case I	Case II
Hyd. sensitivity	M	dB//V/uPa	–196	–190
Hyd. capacitance	Ch	Farad	3000e–12	750e–12
Hyd. Diss. factor	tanδ	–	.005	*
Input capacitance	Ci	Farad	10e–12	*
Input resistance	Ri	Ohm	30e+6	*
Voltage noise	Ea	dB//V/√Hz	–166	*
Ea corner freq.	Fo	Hz	1000	*
Ea slope	a	log(V)/log(Hz)	1	*
Current noise	Ia	dB//A/√Hz	–300	*

* = same as Case I

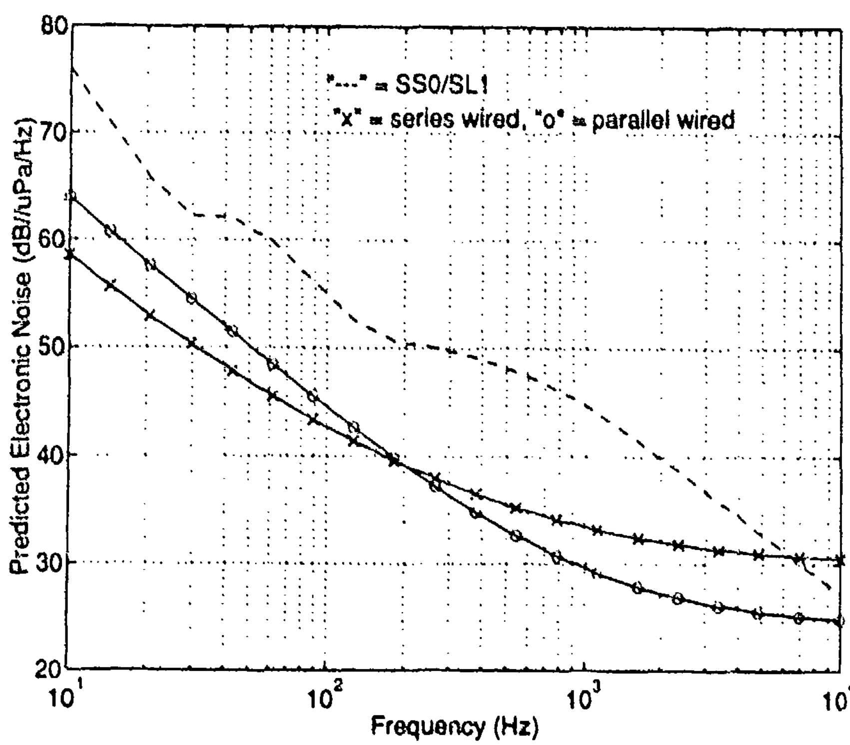


Figure 4. Predicted Noise Versus Hydrophone Wiring Configuration

The second example examines the effect of amplifier input resistance on the total noise referred to the hydrophone input over the frequency range from 10 Hz to 100 kHz. Figure 5 was generated using a modified version of the program "hypA1.m" and subprograms "hypall.m" and "ss0sl1.m" shown in Appendix C.

Table 3. Model Parameters for Effect of Input Resistance on Total Noise

Parameter		Units	Case I	Case II	Case III
Hyd. sensitivity	M	dB//V/uPa	−196	*	*
Hyd. capacitance	Ch	Farad	3000e−12	*	*
Hyd. Diss. factor	tanδ	–	.005	*	*
Input capacitance	Ci	Farad	10e−12	*	*
Input resistance	Ri	Ohm	10e+6	30e+6	100e+6
Voltage noise	Ea	dB//V/√Hz	−166	*	*
Ea corner freq.	Fo	Hz	1000	*	*
Ea slope	a	log(V)/log(Hz)	1	*	*
Current noise	Ia	dB//A/√Hz	−300	*	*

* = same as Case I

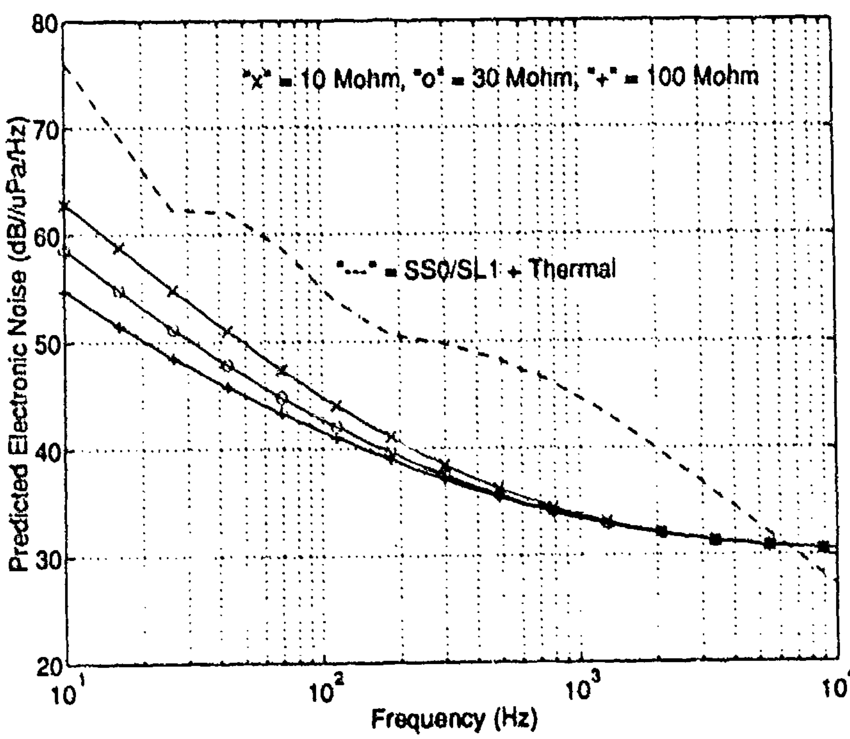


Figure 5. Predicted Noise Versus Amplifier Input Resistance

The third example examines the effect of hydrophone capacitance on the total noise referred to the hydrophone input over the frequency range from 10 Hz to 10 kHz.

Table 4. Model Parameters for Effect of Hydrophone Capacitance on Total Noise

Parameter		Units	Case I	Case II	Case III
Hyd. sensitivity	M	dB//V/uPa	–190	*	*
Hyd. capacitance	Ch	Farad	300e–12	1000e–12	3000e–12
Hyd. Diss. factor	tanδ	–	.005	*	*
Input capacitance	Ci	Farad	10e–12	*	*
Input resistance	Ri	Ohm	30e+6	*	*
Voltage noise	Ea	dB//V/√Hz	–166	*	*
Ea corner freq.	Fo	Hz	1000	*	*
Ea slope	a	log(V)/log(Hz)	1	*	*
Current noise	Ia	dB//A/√Hz	–300	*	*

* = same as Case I

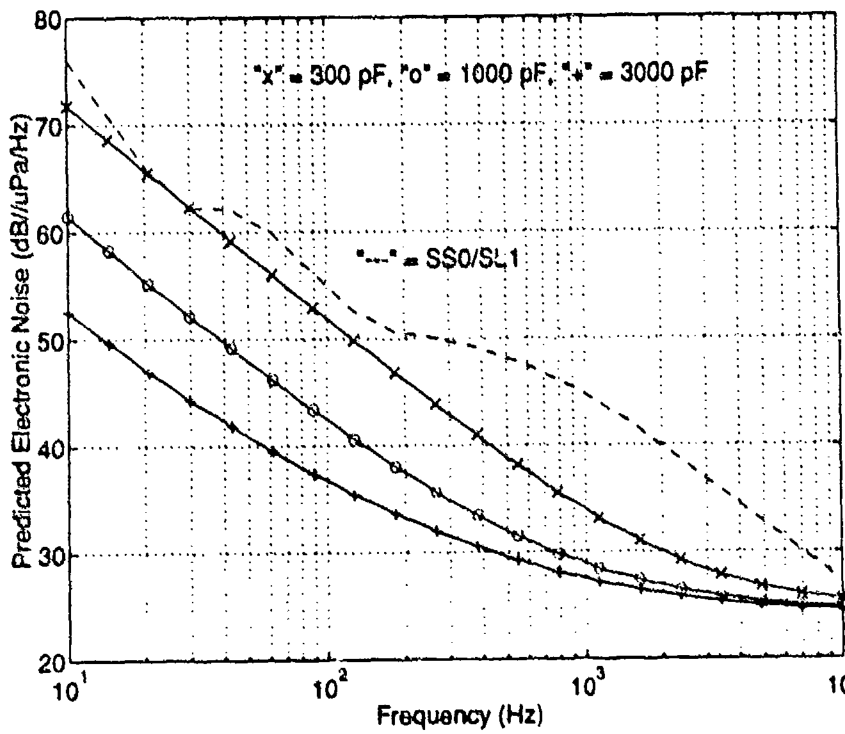


Figure 6. Predicted Noise Versus Hydrophone Capacitance

The fourth example examines the effect of hydrophone dielectric loss tangent on the total noise referred to the hydrophone input over the frequency range from 10 Hz to 10 kHz.

Table 5. Model Parameters for Effect of hydrophone Dielectric Loss on Total Noise

Parameter		Units	Case I	Case II	Case III
Hyd. sensitivity	M	dB//V/uPa	–190	*	*
Hyd. capacitance	Ch	Farad	1000e–12	*	*
Hyd. Diss. factor	$\tan\delta$	–	.005	.015	.045
Input capacitance	Ci	Farad	10e–12	*	*
Input resistance	Ri	Ohm	30e+6	*	*
Voltage noise	Ea	dB//V/√Hz	–166	*	*
Ea corner freq.	Fo	Hz	1000	*	*
Ea slope	a	log(V)/log(Hz)	1	*	*
Current noise	Ia	dB//A/√Hz	–300	*	*

* = same as Case I

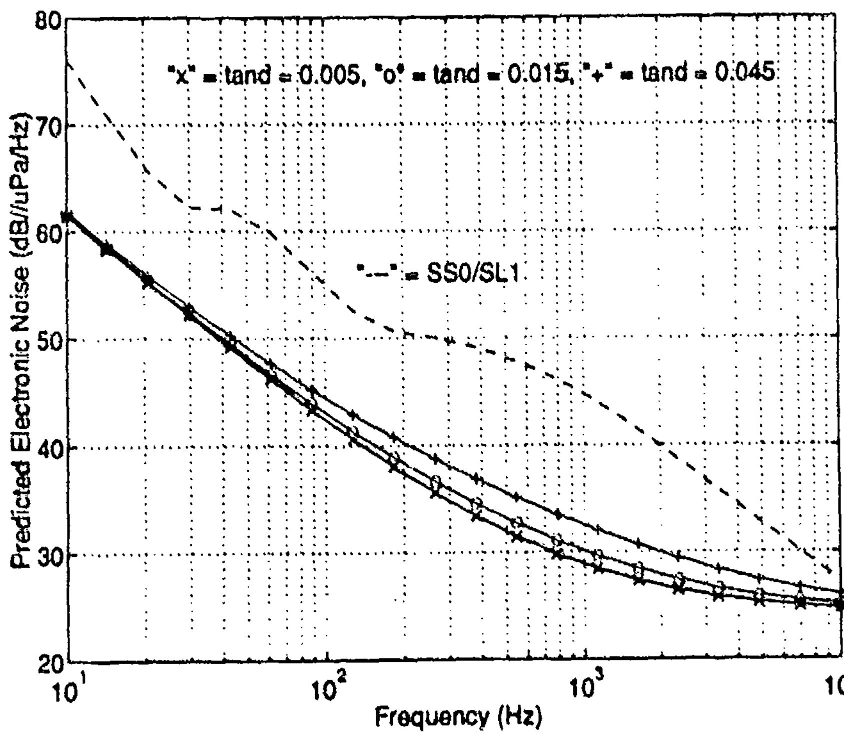


Figure 7. Predicted Noise Versus Hydrophone Dielectric Loss

The fifth example examines the effect of amplifier voltage noise on the total noise referred to the hydrophone input over the frequency range from 10 Hz to 100 kHz.

Table 6. Model Parameters for Effect of Amplifier Voltage Noise on Total Noise

Parameter		Units	Case I	Case II	Case III
Hyd. sensitivity	M	dB//V/uPa	–190	*	*
Hyd. capacitance	Ch	Farad	1000e–12	*	*
Hyd. Diss. factor	tanδ	–	.005	*	*
Input capacitance	Ci	Farad	10e–12	*	*
Input resistance	Ri	Ohm	30e+6	*	*
Voltage noise	Ea	dB//V/√Hz	–166	–160	–154
Ea corner freq.	Fo	Hz	1000	*	*
Ea slope	a	log(V)/log(Hz)	1	*	*
Current noise	Ia	dB//A/√Hz	–300	*	*

* = same as Case I

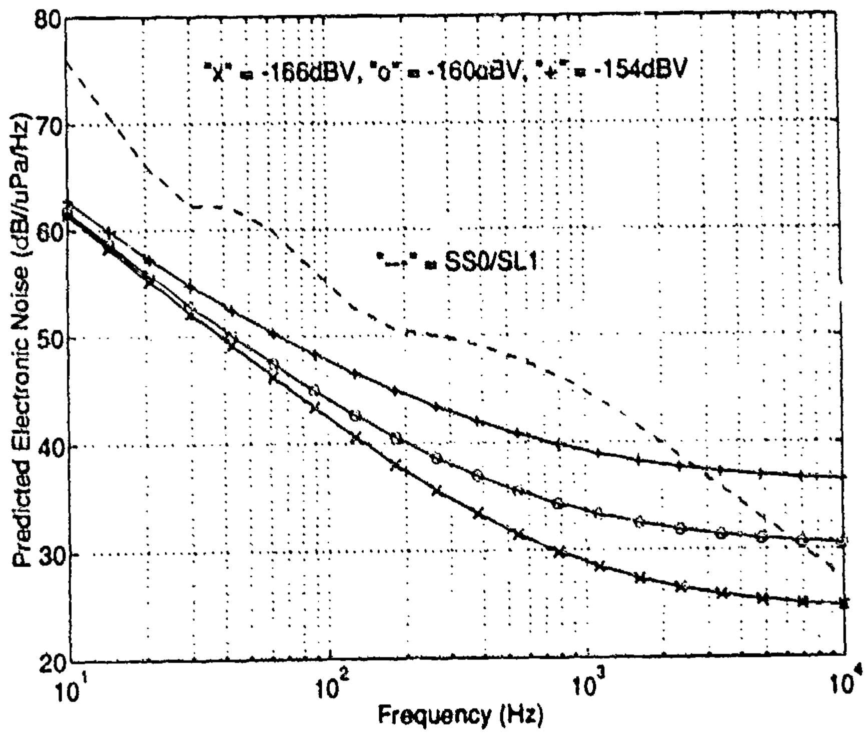


Figure 8. Predicted Noise Versus Amplifier Voltage Noise

The sixth example displays each of the noise sources referred to the hydrophone input over the frequency range from 10 Hz to 10 kHz. In this case only one set of hydrophone and amplifier parameters is used. Figure 6 was generated using a modified version of the program "hypA1.m" and subprograms "hypall.m" and "ss0sl1.m" shown in Appendix C. In figure 9 it can be noted that each of the three noise sources is the dominant noise mechanism over a certain frequency range. The current noise is dominant below 700 Hz, the hydrophone noise is dominant from 700 Hz to 3 kHz, and the voltage noise is dominant above 3 kHz.

Table 7. Model Parameters to Illustrate Individual Noise Components

Parameter		Units	
Hyd. sensitivity	M	dB//V/uPa	–196
Hyd. capacitance	Ch	Farad	300e–12
Hyd. Diss. factor	tanδ	–	.02
Input capacitance	Ci	Farad	10e–12
Input resistance	Ri	Ohm	30e+6
Voltage noise	Ea	dB//V/√Hz	–166
Ea corner freq.	Fo	Hz	1000
Ea slope	a	log(V)/log(Hz)	1
Current noise	Ia	dB//A/√Hz	–300

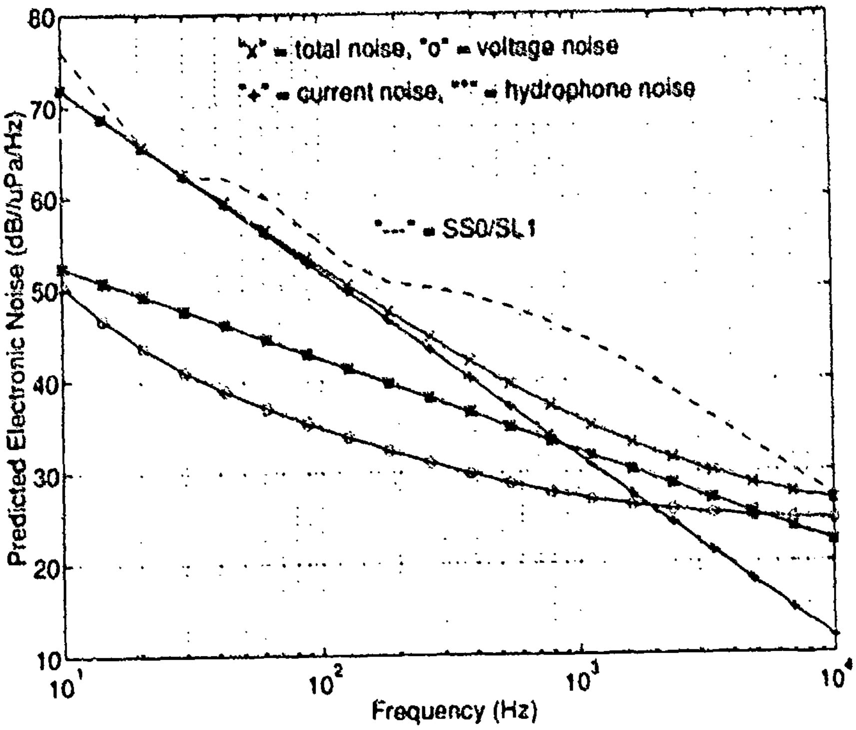


Figure 9. Predicted Individual Noise Components

SIMULATION AND MEASUREMENT EXAMPLES

This section contains two examples of simulations performed using the model and the MATLAB simulator and accompanying measurements on real preamplifiers which had a capacitor simulating the hydrophone impedance. For the first example, the amplifier used a discrete Junction Field Effect Transistor (JFET) source–coupled pair followed by an operational amplifier to provide 40 dB of closed loop gain and a 100 Hz high pass filter response. The JFET's were CD860's and the op amp was an OP–27. The input resistance was 825 Kohm and three values of simulated hydrophone capacitance were used. This amplifier is the high input impedance type and thus the non–inverting amplifier simulation model was used. For the second example, the preamplifier was a custom monolithic integrated circuit preamplifier developed by the author for high frequency, low capacitance applications. This amplifier uses a full differential CMOS operational amplifier with 1.1 picofarad capacitors and 400 Mohm resistors in the feedback paths. This amplifier is the low input impedance, charge amplification type and thus the inverting amplifier simulation model was used. The following two cases were simulated and measured and are shown on the succeeding pages:

7. High input impedance amplifier with CD860's and OP–27 showing the effect of hydrophone capacitance variation on total noise from 10 Hz to 10 kHz. Examples are shown for 1000, 10,000 and 100,000 picofarads.
8. Low input impedance, charge–type amplifier using custom monolithic integrated circuit showing the effect of hydrophone capacitance variation on total noise from 1 KHz to 100 kHz. Examples are shown for 9, 33 and 150 picofarads.

The seventh example examines the effect of hydrophone capacitance on the total noise referred to the hydrophone input over the frequency range from 10 Hz to 10 kHz and includes measurement data from an amplifier constructed with low noise JFET's and a low noise op amp. The simulation model was modified to present noise referred to the amplifier input since a value for hydrophone did not exist. The value for dissipation factor is approximate for these capacitors.

Table 8. Model Parameters for Effect of Hydrophone Capacitance on Total Noise

Parameter		Units	Case I	Case II	Case III
Hyd. sensitivity	M	dB//V/uPa	N/A	*	*
Hyd. capacitance	Ch	Farad	1e–9	10e–9	100e–9
Hyd. Diss. factor	tanδ	–	.001	*	*
Input capacitance	Ci	Farad	20e–12	*	*
Input resistance	Ri	Ohm	825e+3	*	*
Voltage noise	Ea	dB//V/√Hz	–172	*	*
Ea corner freq.	Fo	Hz	1600	*	*
Ea slope	a	log(V)/log(Hz)	1	*	*
Current noise	Ia	dB//A/√Hz	–300	*	*

* = same as Case I

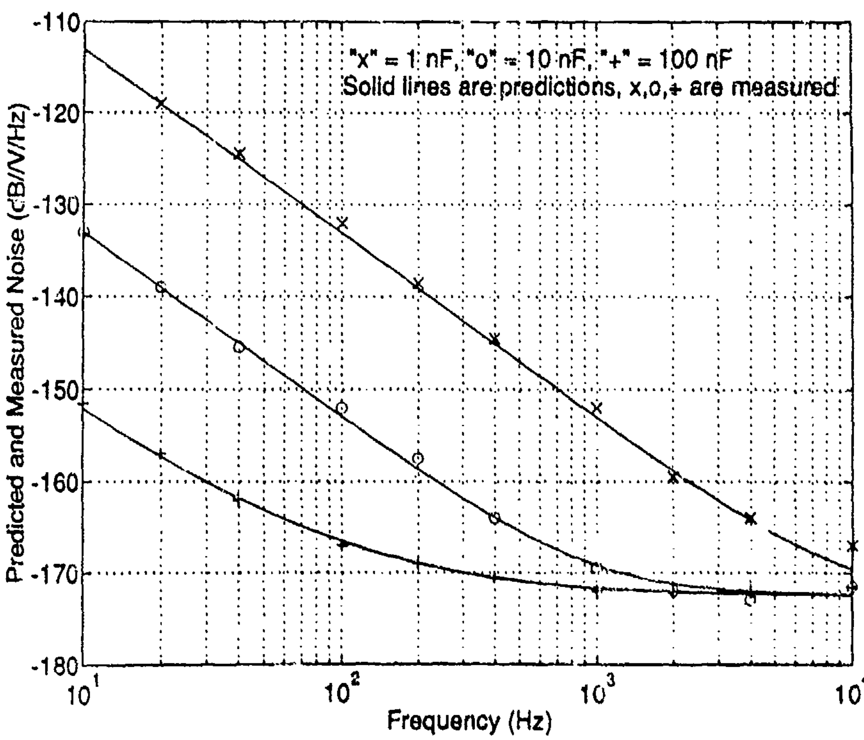


Figure 10. Measured and Predicted Noise Versus Hydrophone Capacitance

The eighth example examines the effect of hydrophone capacitance on the total noise referred to the hydrophone input over the frequency range from 1 kHz to 100 kHz and includes measurement data from an custom monolithic preamplifier amplifier developed by the author. The simulation model was modified to present noise referred to the amplifier input since a value for hydrophone did not exist. The value for dissipation factor is approximate for these capacitors.

Table 9. Model Parameters for Effect of Hydrophone Capacitance on Total Noise

Parameter		Units	Case I	Case II	Case III
Hyd. sensitivity	M	dB//V/uPa	N/A	*	*
Hyd. capacitance	Ch	Farad	9e–12	33e–12	150e–12
Hyd. Diss. factor	$\tan\delta$	–	.001	*	*
Input capacitance	Ci	Farad	10e–12	*	*
Feedback capacitance	Cf	Farad	1.1e–12	*	*
Feedback resistance	Rf	Ohm	400e+6	*	*
Voltage noise	Ea	dB//V/√Hz	–168	*	*
Ea corner freq.	Fo	Hz	3000	*	*
Ea slope	a	log(V)/log(Hz)	1	*	*
Current noise	Ia	dB//A/√Hz	–300	*	*

* = same as Case I

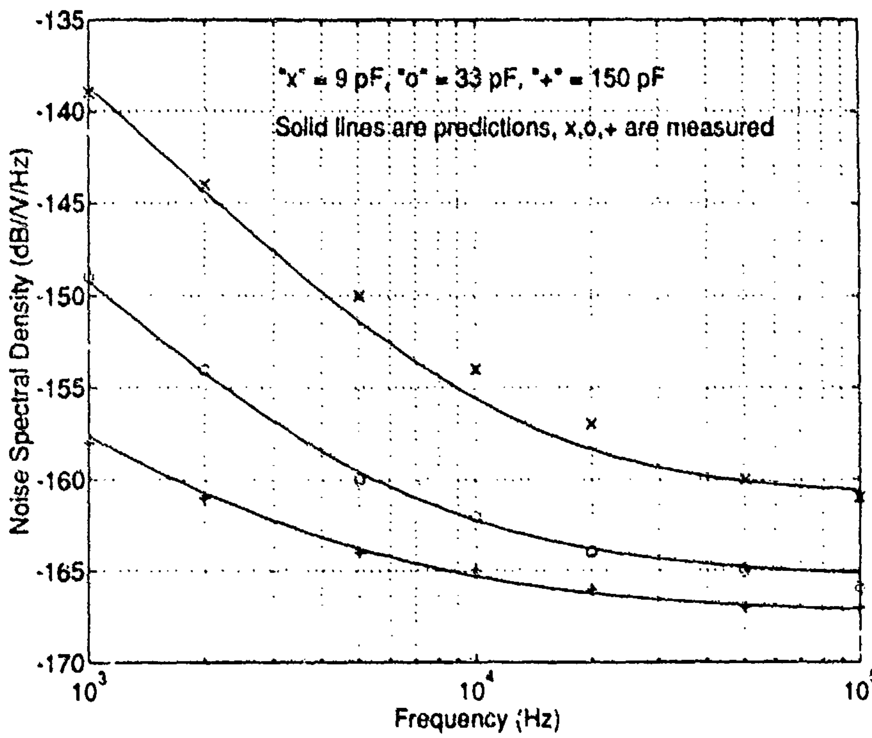


Figure 11. Measured and Predicted Noise Versus Hydrophone Capacitance

SUMMARY AND CONCLUSIONS

A simulation model has been developed for calculating the electronic noise from the combination of an amplifier and a capacitive sensor such as a sonar hydrophone. Two types of amplifier were examined: a non–inverting type with high input impedance and an inverting type with low input impedance and capacitive feedback. Examination of the two amplifier configurations showed nearly identical signal–to–noise ratio. The significant noise sources used in the model are the same for the inverting and non–inverting cases. These noise sources include thermal noise from the hydrophone, thermal noise from resistors, and voltage and current noise from the preamplifier and subsequent stages. A standard ambient acoustic noise model appropriate for deep ocean was described which consists of sea state zero noise, shipping density I noise, low frequency ocean turbulence and molecular agitation noise.

The optimization of electronic noise can be simplified when one noise source is dominant in a given frequency range. For instance, the noise at low frequency is usually dominated by thermal noise from the input resistor (or feedback resistor for the inverting amplifier case).

Eight simulation examples were shown in which hydrophone and/or amplifier parameters were varied. The last two examples showed test measurements in addition to the simulated noise.

RECOMMENDATIONS

This model should be used by the designer prior to actual prototype and test of a system so that the electronic noise performance of a system may be evaluated and so that the pertinent hydrophone and preamplifier performance parameters can be determined and/or verified as being adequate to meet the system requirement. Once a system prototype exists, the system output noise should be measured and divided by the system gain to obtain more correct input noise parameters which can than be used to update the simulations.

The average ambient noise spectra shown in [1] should be used as a standard reference for comparison between various systems and components. By displaying ambient and electronic noise in the water (i. e. in micropascals), direct comparison on one graph can be made between various systems and components.

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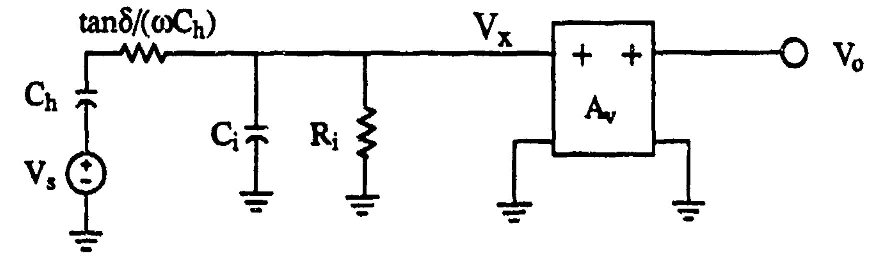
APPENDIX A. NON–INVERTING AMPLIFIER TRANSFER FUNCTION DERIVATION

Figure A–1 shows a circuit model for the impedances and noise sources in a charge–type hydrophone/cable/amplifier system. The hydrophone is modeled as a voltage generator representing the acoustic to electrical transduction, and a capacitor and resistor representing the internal impedance of the hydrophone. The cable is modeled as a capacitance which is lumped with the amplifier input capacitance, C_i. The amplifier is modeled in closed–loop form. Cable leakage resistance is included with the amplifier feedback resistance, R_f.



C_h = Hydrophone capacitance
$\tan\delta$ = Hydrophone dielectric dissipation factor
C_i = Amplifier plus cable input capacitance
R_i = Amplifier input resistance
ω = Frequency
A_v = Amplifier voltage gain
V_s = Hydrophone output signal (electric)
V_x = Amplifier input voltage
V_o = Amplifier Output voltage

Figure A–1. Hydrophone/Cable/Amplifier Model

First, convert the hydrophone and cable circuit into a Thévenin equivalent circuit. Here we can ignore the hydrophone losses since for most hydrophone materials and frequencies of interest $\tan\delta$ is less than 0.1.

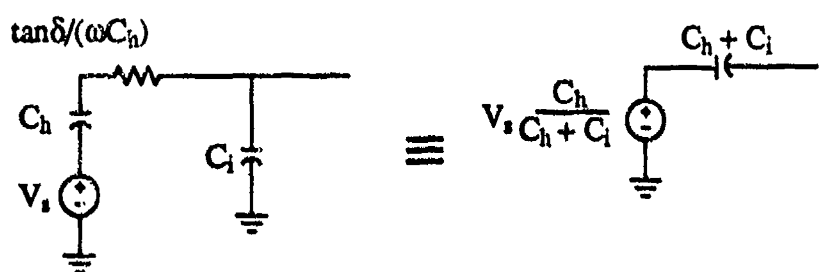


Figure A–2. Hydrophone/Cable Thevénin Equivalent Circuit (tanδ<<1)

Now the hydrophone and input resistor form a simple voltage divider and the voltage V_x can be solved for. We assume that the amplifier input current is zero. Thus,

$$V_x = V_s \left(\frac{C_h}{C_h + C_i}\right) \frac{R_i}{R_i + \frac{1}{j\omega(C_h + C_i)}} . \tag{A1}$$

Solving for the amplifier output voltage:

$$V_0 = A_v V_x , \qquad V_x = \frac{V_o}{A_v} . \tag{A2}$$

Now substitute equation A2 into A1:

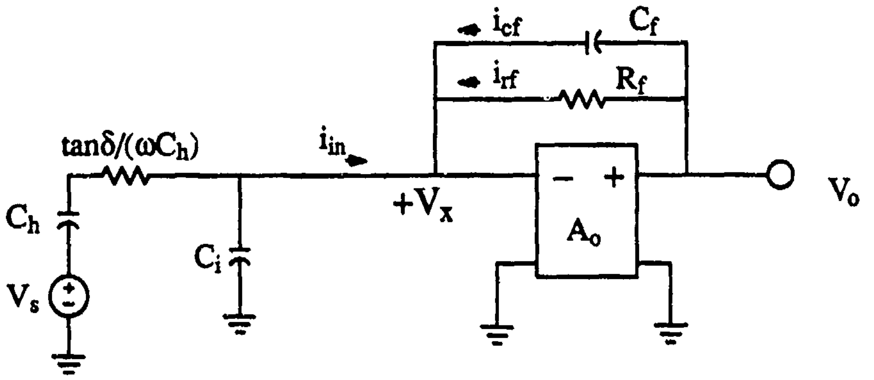
$$\frac{V_o}{A_v} = V_s \left(\frac{C_h}{C_h + C_i}\right) \frac{R_i}{R_i + \frac{1}{j\omega(C_h + C_i)}} . \tag{A3}$$

Rearrange equation A3 to solve for the hydrophone signal transfer function:

$$\frac{V_o}{V_s} = A_v \frac{1}{\frac{C_h + C_i}{C_h} + \frac{1}{j\omega R_i C_h}} . \tag{A4}$$

APPENDIX B. INVERTING AMPLIFIER TRANSFER FUNCTION DERIVATION

Figure B–1 shows a circuit model for the impedances and noise sources in a charge–type hydrophone/cable/amplifier system. The hydrophone is modeled as a voltage generator representing the acoustic to electrical transduction, and a capacitor and resistor representing the internal impedance of the hydrophone. The cable is modeled as a capacitance which is lumped with the amplifier input capacitance, C_i. The amplifier is modeled in closed–loop form. Cable leakage resistance is included with the amplifier feedback resistance, R_f.



C_h = Hydrophone capacitance
$\tan\delta$ = Hydrophone dielectric dissipation factor
C_i = Amplifier plus cable input capacitance
C_f = Amplifier feedback capacitance
R_f = Amplifier feedback resistance
ω = Frequency
A_o = Amplifier open loop gain
V_s = Hydrophone output signal (electric)
V_x = Voltage at amplifier summing node
i_{in} = Current from hydrophone/cable combination
i_{cf} = Current from feedback capacitor
i_{rf} = Current from feedback resistor

Figure B–1. Hydrophone/Cable/Amplifier Model

First, convert the hydrophone and cable circuit into a Thévenin equivalent circuit. Here we can ignore the hydrophone losses since for most hydrophone materials and frequencies of interest $\tan\delta$ is less than 0.1.

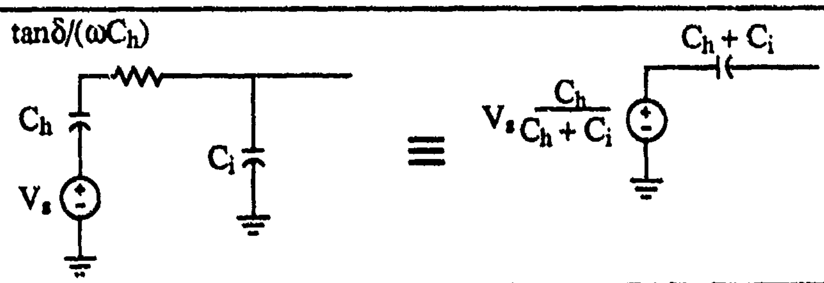


Figure B–2. Hydrophone/Cable Thévenin Equivalent Circuit ($\tan\delta$<<1)

Second, sum the currents at the summing node, Vx using Kirchoff's current law. Assume that the amplifier input current is zero. thus,

$$i_{in} + i_{cf} + i_{rf} = 0.$$

Third, substitute the voltage across each element times the element admittance in the above equation tp obtain

$$\left(V_s \frac{C_h}{C_h + C_i} - V_x\right) j\omega\left(C_h + C_i\right) + \left(V_o - V_x\right)\left[j\omega C_f + \frac{1}{R_f}\right] = 0. \qquad \text{(B1)}$$

Fourth, solve for the amplifier output voltage:

$$V_o = -A_o V_x , \qquad V_x = -\frac{V_o}{A_o} . \qquad \text{(B2)}$$

Now substitute equation B2 into B1:

$$\left(V_s \frac{C_h}{C_h + C_i} + \frac{V_o}{A_o}\right) j\omega\left(C_h + C_i\right) + \left(V_o + \frac{V_o}{A_o}\right)\left[j\omega C_f + \frac{1}{R_f}\right] = 0. \qquad \text{(B3)}$$

In the second term of equation B3, if we assume that $A_o >> 1$, then the V_o/A_o portion can be ignored. After making this assumption and collecting terms, the following results:

$$V_s\, j\omega C_h + \frac{V_o}{A_o} j\omega\left(C_h + C_i\right) + V_o j\omega C_f + V_c \frac{1}{R_f} = 0 \qquad \text{(B4)}$$

Now solve equation B4 for the hydrophone signal transfer function, V_o/V_s:

$$\frac{V_o}{V_s} = \frac{-j\omega C_h}{j\omega C_f + \frac{1}{A_o} j\omega\left(C_h + C_i\right) + \frac{1}{R_f}} . \qquad \text{(B5)}$$

Rearranging equation B5 results in a more useful expression for the hydrophone signal transfer function

$$\frac{V_o}{V_s} = \frac{C_h}{C_f} \frac{-1}{1 + \frac{1}{A_o}\left(\frac{C_h + C_i}{C_f}\right) + \frac{1}{j\omega R_f C_f}} . \qquad \text{(B6)}$$

APPENDIX C. MATLAB LISTINGS

MATLAB (version 3.5i) listing of the main program for calculating and plotting hydrophone and amplifier noise as well as ambient ocean noise versus frequency.

```
%  Hydrophone and preamplifier noise  --  main program
%  Last edit:  22 Feb 93      T. B. Straw
clear; clg; subplot(111)
N = 20;  %  Number of frequency points
f  =  logspace(1, 4, N);  %  Frequency axis vector
% ---- Typical preamp parameters
Ea = -166;          % Voltage Noise in dB//V/Hz
Fo = 1000;          % Voltage Noise corner frequency
a  = 1;             % Voltage Noise slope
Ia = -300;          % Current Noise in dB//A/Hz
Ri = 30e+6;         % Preamp input resistance (ohm)
Ci = 10e-12;        % Preamp input + cable capacitance (farad)
%  ---- Hydrophone #1 parameters
M1 = -196;          % Hydrophone sensitivity (dB//V/uPa)
C1 = 3000e-12;      % Hydrophone capacitance (farad)
T1 = 0.005;         % Hydrophone dissipation factor
%  ---- Hydrophone #2 parameters
M2 = -190;          % Hydrophone sensitivity (dB//V/uPa)
C2 = 750e-12;       % Hydrophone capacitance (farad)
T2 = 0.005;         % Hydrophone dissipation factor
% ---- calculate per channel ambient noise and the noise spec
%   notes: - SN and Stherm are in units of dB//uPa/Hz
%          - SN is the sum of turbulence, shipping and sea state noise
%          - Stherm is thermal noise (significant above 30 kHz)
[SN, Stherm] = ss0sl1(f);
SMAX = max(SN,Stherm);
%  Calculate electronic noise components
%   notes: - STx is total electronic noise in units of dB//V/Hz
%               (where x stands for Hydrophone #1 or #2)
%          - SEx, SIx, and SHx are the preamp voltage noise, current noise,
%       and hydrophone noise respectively, referred to the hydrophone output.
[ST1,SE1,SI1,SH1] = hypall(f,Ri,Ci,Ea,Fo,a,Ia,C1,T1);
[ST2,SE2,SI2,SH2] = hypall(f,Ri,Ci,Ea,Fo,a,Ia,C2,T2);
%  Power sum thermal (water) noise with electronic noise and convert to dB
SNT1 = 10*log10(10 .^((ST1-M1)/10) + 10 .^(Stherm/10));
SNT2 = 10*log10(10 .^((ST2-M2)/10) + 10 .^(Stherm/10));
%  Plot predicted electronic noise for each case and plot the noise spec
axis([1 4 20 80]);
semilogx(f', SMAX,'--'); hold on; grid;
semilogx(f', SNT1); semilogx(f', SNT1, 'x');
semilogx(f', SNT2); semilogx(f', SNT2, 'o'); hold off
xlabel('Frequency (Hz)'); ylabel('Predicted Electronic Noise dB//uPa/Hz')
gtext('"---" = SS0/SI1');
gtext(' "x" = series wired, "o" = parallel wired')
```

MATLAB listing for the subroutine which calculates Sea State 0, Shipping Level I, Ocean Turbulence plus Molecular Agitation.

```
  function [SN,STH] = ss0sl1(f)
% SS0SL1  Calculates the sea state 0, shipping level I ambient noise
%            including low frequency turbulence and high frequency
%            molecular agitation noise.
%         Based on equations in NUSC TD7265 "Ambient Noise
%            Standards for Acoustic Modeling and Analysis"
% usage: [SN,STH] = ss0sl1(f)
%      SN  = output vector of Sea State 0, shipping level I, ocean turbulence
%            noise versus frequency (dB//uPa/Hz)
%      STH = output vector of Thermal Noise vs frequency (dB//uPa/Hz)
%      f   = Input vector of frequencies
% NOTE: In order to keep the model general, these numbers are presented
%       in units of dB//uPa/Hz.
%    Last edit: 22 Feb 93     T. B. Straw
%
lf = log10(f);
r  = size(f);
N  = r(2);
         %%%%%%% ocean turbulence noise
S1  = 108.5 -32.5*log10(f);
         %%%%%%% shipping level I noise
for n = 1:N;
   if f(:,n) <= 42,
      C0 = 43.77; C1 = -0.297; C2 = 24.449; C3 = -10.671;
   elseif f(:,n) <= 167,
      C0 = -341.201; C1 = 660.506; C2 = -351.319; C3 = 60.060;
   else
      C0 = 0; C1 = 0; C2 = 0; C3 = 0;
   end
   S2(:,n) = C0 + C1*lf(:,n) + C2*lf(:,n).^2 + C3*lf(:,n).^3;
end
         %%%%%%% sea state noise
s = 0;  % sea state 0
g = -(s - 1)*(-0.805*s + 7.460)/7.460;

for n = 1:N;
   if f(:,n) <= 167,
      S3(:,n) = 0;
   elseif f(:,n) <= 1657,
      S3(:,n)  = 50.372 + 0.861*s - 1.899*s^2 + 0.172*s^3 ...
         + 0.871*lf(:,n) - 0.117*lf(:,n).^4 + 5.758*s.*lf(:,n) ...
         - 0.746*s.*lf(:,n).^2 - 0.106*s^2.*lf(:,n) - 17.4*g ...
         + 14.616*g.*lf(:,n) - 2.791*g.*lf(:,n).^2;
   else
      S3(:,n) = 99.71 - 18.114 .*lf(:,n);
   end
end
S4 = max(S1,S2);
SN = max(S3,S4); % Total of Sea State plus Shipping plus turbulence
         %%%%%%% Thermal (molecular agitation) noise
STH  = -75 + 20*log10(f);
```

MATLAB listing for the subroutine which calculates hydrophone and preamplifier electronic noise (Non–inverting type of preamplifier)

```
function [ST,SE,SI,SH] = hypall(f,Ri,Ci,Ea,Fo,a,Ia,Ch,td)
% HYPALL  Calculates hydrophone and preamp noise for the
%            non-inverting preamplifier configuration. Returns
%            total noise and individual noise components
%
%    Last edit: 13 Mar 92     T. B. Straw
%
%    usage: [ST,SE,SI,SH] = hypall(f,Ri,Ci,Ea,Fo,a,Ia,Ch,td)
%    ST  = Total noise versus frequency referred to hydrophone output
%    SE  = Voltage noise referred to hydrophone output
%    SI  = Current noise referred to hydrophone output
%    SH  = Hydrophone noise
%    f   = input vector of frequencies (Hz)
%    Ri  = Input Resistance  (Ohm)
%    Ci  = Parasitic + input Capacitance (Farad)
%    Ea  = Preamp voltage noise (dB//V^2/Hz)
%    Fo  = Preamp voltage noise corner freq (Hz)
%    a   = Preamp voltage noise slope
%    Ia  = Preamp current noise (dB//A^2/Hz)
%    Ch  = Hydrophone capacitance (Farad)
%    td  = Hydrophone dissipation factor
w   = 2*pi*f;                  % Radian frequency
fKT = 1.6e-20;                 % 4 * Boltsmann constant * Temp (25C)
Zh  = 1 ./ (w * Ch);           % Hydrophone impedance
ia  = 10^(Ia/10);              % Voltage noise (V^2/Hz)
ea  = 10^(Ea/10);              % Current noise (A^2/Hz)
        % Hydrophone thermal noise
sh  = fKT * td .* Zh;
SH  = 10*log10(sh);
        % amplifier voltage noise (includes 1/f noise)
se  = (((Ch+Ci)/Ch).^2 + 1 ./(w*Ri*Ch).^2).*ea.*(1+(2*pi*Fo./w).^a);
SE  = 10*log10(se);
        % input resistor plus amplifier current noise
si =(fKT*Ri+ia.*Ri^2)./(1+(w*Ri*(Ch+Ci)).^2).*((1+Ci/Ch)^2+1 ./(w*Ri*Ch).^2);
SI  = 10*log10(si);
        % power sum of all noise components
st  = sh + si + se;
ST  = 10*log10(st);
```

MATLAB listing for the subroutine which calculates hydrophone and preamplifier electronic noise (Inverting type of preamplifier)

```
function [ST,SE,SI,SH] = chga(f,Rf,Cf,Ci,Ea,Fo,a,Ia,Ch,td)
% CHGA  Calculates hydrophone and preamplifier noise for the
%               charge sensitive preamplifier configuration (such as the
%               monolithic preamplifier 'gamma')
%
%    Last edit: 3 Mar 93     T. B. Straw
%
%    usage: [ST,SE,SI,SH] = chga(f,Rf,Cf,Ci,Ea,Fo,a,Ia,Ch,td)
%  Outputs:
%    ST  = total noise versus frequency
%    SV  = voltage noise
%    SI  = current noise
%    SH  = hydrophone noise
%  Inputs:
%    f   = array of input frequency
%    Rf  = Feedback Resistance  (Ohm)
%    Cf  = Feedback Capacitance   (F)
%    Ci  = Cable + amplifier input Capacitance (F)
%    Ea  = Preamp voltage noise floor (dB//V^2/Hz)
%    Fo  = Preamp voltage noise corner frequency (Hz)
%    a   = Preamp voltage noise exponent
%    Ia  = Preamp current noise floor (dB//A^2/Hz)
%    Ch  = Sensor capacitance (Farad)
%    td  = Sensor dissipation factor
w   = 2*pi.*f;              % Radian frequency
fKT = 1.6e-20;              % 4 * Boltsmann constant * Temp (273 K)
Zh  = 1 ./ (w * Ch);        % Sensor impedance
         % Sensor thermal noise
sh  = fKT * td .* Zh;
SH  = 10*log10(sh);
         % Feedback resistor noise plus amplifier current noise
sr  = (fKT./Rf + Ia^2).*Zh.*Zh;
SI  = 10*log10(si);
         % amp voltage noise
se                                  =                 10^(Ea/10)*(1+Fo./
f).^a*(((Ch+Ci+Cf)./Ch).^2).*(1+1./(w*Rf*(Ch+Ci+Cf)).^2);
SE  = 10*log10(se);
         % Total noise
st  = sh + si + se;
ST  = 10*log10(st);
```

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